

# **A Demonstration of Radio Interferometric Surveying Using DSS 14 and the Project ARIES Transportable Antenna\***

K. M. Ong, P. F. MacDoran, J. B. Thomas, H. F. Fliegel, L.  
J. Skjerve, and D. J. Spitzmesser  
Tracking and Orbit Determination Section

P. D. Batelaan  
Communications Elements Research Section

S. R. Paine  
DSN Engineering Section

M. G. Newsted  
Trend Western Corporation

*A precision geodetic measurement system (ARIES for Astronomical Radio Interferometric Earth Surveying) based on the technique of very long baseline interferometry has been designed and implemented through the refurbishment of a 9-m transportable antenna, together with the 64-m Goldstone antenna (DSS 14) of the Deep Space Network. A series of experiments designed to demonstrate the inherent accuracy of the transportable interferometer concept was performed on a 307-m baseline during the period from December 1973 to June 1974. This short baseline was chosen in order to obtain a comparison with a conventional survey with few-centimeter accuracy and to minimize interferometry errors due to transmission media effects, source locations, and Earth orientation parameters. These interferometry measurements, representing approximately 28 hours of data, were in excellent agreement with the survey baseline in all dimensions within the formal uncertainty of 3 cm. The ARIES transportable antenna has now entered its next phase of demonstrations over a 180-km baseline (Goldstone to JPL) and has initiated a tectonic motion monitoring program within the southwestern United States.*

---

\* This report presents the results of one phase of research sponsored by the Office of Applications, Earth and Ocean Physics Applications Program, Project ARIES. It is being made available in this forum because of the essentialness of the available DSN facilities for this work and of the potential usefulness of radio interferometry to future DSN development.

## I. Introduction

In recent years, the technique of independent-station radio interferometry (commonly called "very long baseline interferometry" or VLBI) has been continuously developed and to some degree successfully applied to the problem of accurately determining baseline vectors between fixed reference points on Earth relative to an "inertial" coordinate system defined by the virtually time-invariant directions of extragalactic radio sources. Astronomers and geophysicists alike have been enthusiastic about the use of this new technique as an accurate geodynamic/geodetic measurement tool.

Since other interferometry baseline measurements (e.g., Refs. 1-4) have been summarized elsewhere (e.g., Ref. 5), they will not be discussed in detail here. All of those previous VLBI experiments utilized non-portable antennas that, unfortunately, lack the mobility that would be required in an extensive geodetic monitoring program. For example, a program to thoroughly monitor global plate tectonics or even a regional strain field, such as in the seismically active Southern California region, would require accurate geodetic measurements of many reference baselines. Furthermore, in a test of the recently advanced dilatancy/diffusion model for earthquakes (Refs. 6-8), it would be especially important to be able to make frequent measurements in three dimensions in areas that are suspected of dilatant behavior. Since it is not economically feasible to build a large network of fixed interferometer antennas all over the world to monitor such complex crustal motions, the question arises whether accurate interferometric surveying is possible with a system in which one element, or perhaps both elements, of the interferometer are transportable, as described in Ref. 9.

In pursuit of this question, a preliminary signal-to-noise analysis at the Jet Propulsion Laboratory (JPL) indicated that, with existing low-noise receivers, an antenna with a diameter of approximately 10-m could be used in conjunction with the Goldstone Mars Deep Space Station (DSS 14) 64-m antenna, provided that the incoming radio signals were recorded with a relatively wide bandwidth (greater than  $\sim 2$  MHz). Fortunately, a wide-band recording system with a 2-MHz bandwidth already existed at the time in the form of the Mark II Very Long Baseline (VLB) System of the National Radio Astronomy Observatory (NRAO) (Ref. 10). Consequently, under Project ARIES (for Astronomical Radio Interferometric Earth Surveying), a surplus U.S. Army 9-m transportable satellite communications station was obtained and modified at JPL for the specific purpose of demonstrating independent-station interferometry with a portable antenna. The

transportable antenna, which will be referred to as the ARIES station, was made ready for its first interferometry experiments in the fall of 1973.

Before the technique of independent-station interferometry, including portable-antenna interferometry, can gain acceptance as a valuable geodetic/geodynamic measurement tool, a series of demonstration experiments are first required to establish its reliability and accuracy at the centimeter level. Among the many possible demonstrations, a short baseline experiment is one of the most effective for several reasons, as summarized by Thomas et al. (Ref. 5). Briefly, short baseline interferometry experiments can lead to accurate three-dimensional, Earth-fixed baseline measurements that expose and therefore effectively test many potential interferometer problems. More importantly, a geometrically complete, centimeter-level accuracy demonstration is possible for a short baseline since conventional survey techniques can measure short baselines in three-dimensions with accuracies at the centimeter level.

In addition to demonstrating portable station interferometry, the present experiments were motivated by the difficulties encountered in comparing survey and interferometry baselines at the 10- to 20-cm level during the analysis of the 16-km Goldstone experiments (Ref. 5). The accuracy of that comparison was significantly degraded by survey uncertainties due to geoid variations and possible interferometer instrumental effects. Since an independent accuracy check was desired, an even shorter baseline demonstration was conducted in which geoidal uncertainties were less significant. Thus, the ARIES antenna was placed approximately 307 meters away from the 64-m antenna for these portable antenna demonstrations. (See photograph, Fig. 1. The apparent relative size of the antennas is inaccurate due to the difference in their distances from the camera. The true sizes of the antennas may be visualized by noting that the subreflector of the Mars antenna is approximately the same diameter as the ARIES antenna.)

In summary, the purpose of this series of ARIES 307-m baseline experiments was to demonstrate the following capabilities of independent-station radio interferometric surveying:

- (1) Attainment of few-centimeter *formal uncertainties* in three dimensions.
- (2) Demonstration of few-centimeter *accuracy* in three dimensions by comparing with a conventional survey.
- (3) Accurate measurement of small known changes in the baseline vector.

## II. Instrumentation

Even though the basic concepts behind radio interferometry are ostensibly simple, the details involved in instrumentation, data reduction, and analysis are quite involved. Since many of these aspects of interferometry have been amply described elsewhere (e.g., Refs. 5 and 11-17), attention will be focused primarily on the features that are specific to the present transportable system.

The present system employs the Goldstone 64-m Mars antenna with an operational system noise temperature of 20-50 K and an efficiency of approximately 0.55, in conjunction with the transportable 9-m ARIES antenna with a system noise temperature of approximately 200 K and efficiency of 0.50. The system noise at ARIES was added almost entirely at the first stage of amplification, while for the Mars antenna, it was a sum of instrumental noise, background radio-frequency noise, and source noise. The group delay variation effect experienced at the Mars station in previous measurements (Ref. 5) has been overcome for the present experiments by the use of a superconducting magnetic shield surrounding the traveling-wave maser amplifier.

As illustrated in Fig. 2, a fixed and transportable antenna pair simultaneously receive random radio signals emitted by a compact extragalactic radio source. Because of a difference in the raypaths from the extragalactic radio source to each station, reception of the signals will be delayed at one antenna relative to the other. This "geometric delay,"  $\tau_g$ , and its time derivative (proportional to the so-called "fringe frequency,"  $\nu_f$ ) are the primary observables of an interferometer. Both quantities are sensitive functions of the baseline vector between the two antennas. Therefore, by observing many different radio sources widely spread over the sky, one can obtain an accurate three-dimensional determination of the baseline vector by means of a simultaneous least-squares fit to the ensemble of measured delay and fringe frequency values. In the present experiments, the delay measurements are the main observables.

There is, at each station, a very stable frequency reference that is used to derive the local oscillator signals for the radio receivers and to drive the station clock. At the ARIES station, a Hewlett-Packard rubidium (HP5065A) oscillator served as the frequency reference for the local oscillator and the timing signals; at the Mars station, a JPL hydrogen maser was used. The radio receiver output is digitally sampled and time-tagged according to the clock signals. This stream of time-tagged digital data is then input to a magnetic tape recorder at

each station. In the present implementation, the NRAO Mark II 4-Mbit/s recording system (Ref. 10) is used.

In order to determine the time delay observable with high precision, the extragalactic radio signals are recorded in two separate frequency channels and the so-called "bandwidth synthesis" technique (Refs. 13 and 18) is employed. In the present ARIES system, the signals were received at two 2-MHz frequency bands centered at 2311 and 2271 MHz, and recorded on alternate seconds at a 4-Mbit/s rate using Mark II terminals at each site. A block diagram of the system configuration is shown in Fig. 3. The delay values produced by this system possessed uncertainties due to system noise that ranged between 0.05 and 0.5 ns for correlated flux strengths between 2 and 20 Jy. (1 Jy  $\equiv$  1 Jansky  $\equiv$  1 flux unit  $= 1 \times 10^{-26}$  watts/m<sup>2</sup>/Hz.) The techniques of extracting the time delay and fringe frequency observables will be discussed next.

## III. Data Reduction Technique

In these ARIES experiments, about a dozen compact radio sources were observed simultaneously at the two antennas in 20-30 separate scans of approximately 10-minute duration over a total time span of 6-10 hours. After each experiment, the 5-cm-wide video tapes on which the data were recorded at each station were brought together for digital cross correlation using the Mark II Processor Playback System at NRAO, Charlottesville, Virginia (Ref. 10). The resulting post-correlation computer tapes, which contain the highly compressed data usually referred to as "stopped fringes," were then taken back to JPL for further reduction and analysis with an IBM 370 computer at the California Institute of Technology. The data reduction software for fringe processing, which was designed and developed at JPL for the IBM 370, extracts the phase as a function of time (phase tracking), refines the phase model used for "stopping the fringes" in the Mark II Processor, and obtains the delay (by two-channel bandwidth synthesis) for each radio source observed. The delay model, phase model, phase tracking, bandwidth synthesis techniques, and radio source locations used for these experiments are essentially the same as those employed for the 16-km Goldstone experiments detailed in Refs. 5 and 13, and will not be described here.

Each measured delay value can be modeled as a sum of a geometric delay, instrumental delays, and any differential delays due to the transmission media. For the present system, the instrumental delay terms can, in the ideal case, be collectively modeled as a constant offset ("clock offset") and a linear drift ("clock rate difference"), but must

sometimes be given a more complicated form to account for oscillator instabilities. As mentioned earlier, for a baseline that is only 307 meters in length, the transmission media delays should be nearly equal along the two raypaths so that they virtually cancel out in the measured delay. Furthermore, relative to other delay uncertainties, the geometric delay for this baseline is insensitive to source location and Earth orientation errors at the arc second level. Since the relevant source locations and Earth orientation parameters have been independently measured at the 0.03–1.0 arc second level, they are more than adequate for the present experiments.

Based on the above model, the delay values collected on a given day can be simultaneously fit by means of a weighted least-squares procedure (Ref. 5) in which the three baseline components and two instrumental parameters (in the ideal case) are “solve-for” parameters. Quoted (“formal”) errors in these solve-for quantities are estimated by means of a covariance analysis based on post-fit residuals.

#### IV. Conventional Survey of the 307-m Baseline

Over a 7-month period the ARIES transportable station occupied two different positions separated by about 0.5 m, approximately 307-m east-southeast of the Mars station. The site occupied before January 16, 1974 is called Site A, and the other is called Site B. The baseline vector between the two antennas is most conveniently defined to be the vector extending from the intersection of the azimuth and elevation axes of one antenna to the corresponding point on the other antenna. This vector has been measured by means of local surveys in terms of geodetic coordinates and then transformed to the Conventional International Origin (CIO) frame. (In the CIO frame, the z-axis points toward the 1903.0 mean pole, the x-axis toward the Greenwich meridian, while the y-axis completes a right-handed coordinate frame.) The conventional surveys were performed with respect to a first-order control point (MARS  $\Delta$ ) established by the U. S. Coast and Geodetic Survey (now the National Geodetic Survey) in 1966. An additional control point (ARIES  $\Delta$ ) was placed near the ARIES antenna. The baseline vector between antennas was then obtained by combining three separate conventional surveys: Teledyne, Inc. for MARS  $\Delta$  to MARS antenna in 1966; M&Q Pacific for MARS  $\Delta$  to ARIES  $\Delta$  in 1974; and JPL for ARIES  $\Delta$  to ARIES antenna in 1974. The resulting survey baseline coordinates, which have been transformed to the CIO frame, are presented in Table 1 along with their estimated errors ( $1\sigma$ ).

#### V. Interferometry Results and Comparison With Survey

During the period from December 1973 to June 1974, four successful interferometry experiments between the ARIES transportable antenna and the 64-m Mars station were conducted. The first of these experiments (on December 22, 1973) was performed with the ARIES antenna at its Site A position, whereas the Site B position was occupied for all subsequent experiments. For each experiment, an attempt was made to fit the measured delay values with the “ideal” five-parameter model discussed above. However, because of oscillator instabilities in these experiments, it was found that either 6 or 7 parameters were necessary in order to obtain good fits to the measured delay values. In the December 22, 1973, April 24, 1974, and June 18, 1974 experiments, the rubidium oscillator apparently underwent an abrupt frequency shift in the midst of the observations so that independent parameters for both the offset and the clock-rate (giving a 7-parameter fit) were required on either side of the discontinuity. On the other hand, in the June 5, 1974 experiment, which contained approximately 10 hours of data, the oscillators behaved well enough so that all 29 delay measurements could be fit by 6 parameters (the 5 “ideal” parameters plus a frequency rate parameter). Delay residuals for this last experiment are given in Fig. 4. For each experiment, an analysis of post-fit residuals revealed the presence of unmodeled noise in addition to known system noise. Therefore, an extra noise term, estimated on the basis of the  $\chi^2$ -analysis, was included in the final least-squares solution for the baseline and instrumental parameters (Ref. 5). The source of this extra-noise term was possibly the unmodeled short-term ( $\approx 1$  hour) instability of the rubidium oscillator. A summary of each experiment, including root-mean-square delay residuals and the unmodeled noise level for each experiment, is given in Table 2. The resultant baseline vectors are given in Table 3, where a weighted average of all Site B solutions is also included.

Table 4 compares the displacement vector (Site B–Site A) as derived from the combined interferometry data with the one derived from survey. It is seen that the two methods are in good agreement within the data noise level of 8 cm. (The relatively large data noise is due mainly to the 7-cm uncertainty in the Site A interferometry solution.)

A summary of the interferometry results and a comparison with the survey is given in graphical form in Fig. 5. Note that the December 1973 experiment, which was performed with the ARIES antenna at Site A, has

been adjusted to the Site B position by use of the accurately determined survey displacement vector. The bracketed values represent the weighted averages of the last three Site B measurements.

One important feature of these particular interferometry results is that in some cases the error in the Y-component of the baseline vector is larger than the other components, both in terms of its formal error estimate and in terms of the agreement with the survey. This Y-component weakness was caused by an inadequate geometric distribution of source directions, due either to poor observing strategy or to the loss of scheduled observations. It should be possible to design future measurements so that this weakness is eliminated.

## VI. Conclusions

These measurements completed the first phase of a series of Project ARIES experiments designed to demonstrate the suitability of a transportable, independent-station radio interferometric system for accurate geodetic measurements. In this first phase, a 307-m baseline near the 64-m Mars station at Goldstone has been surveyed both conventionally and interferometrically. Results of these experiments show that the transportable interferometer possesses an inherent accuracy of a few centimeters in three dimensions for short baselines, and is a potentially powerful geodetic measurement tool. Specifically, the following capabilities of the present transportable radio interferometer have been demonstrated for a 307-m baseline:

- (1) With approximately 28 hours of observations, a formal uncertainty (precision) of 3 cm in each component of the baseline can be achieved.
- (2) Comparison of the interferometer baseline with conventional survey indicates that the 3-cm precision can be regarded as the *accuracy* of the system.
- (3) The interferometer has successfully detected a small intentional change in baseline with approximately 8-cm accuracy. This relatively large uncertainty was due mainly to the single six-hour measurement of the Site A position.

In addition, these ARIES experiments have isolated and demonstrated at the few-centimeter level the following performance of the instrumental and analytic subsystems on the 307-m baseline:

- (1) The achievement of an adequate signal-to-noise ratio for delay measurements using the 9-m/64-m interferometer system with a 4-Mbit/s record rate.

- (2) The experimental evaluation of oscillator instability in terms of bandwidth synthesis and baseline vector solutions. In this regard, we have found that the rubidium frequency standard is marginally adequate.
- (3) The successful integration of the NRAO 2-MHz-bandwidth Mark II digital recorder and cross-correlation system.
- (4) The adequacy of the group delay stability of the interferometer instrumentation.
- (5) The adequacy of the two-channel bandwidth synthesis subsystem.
- (6) The development and validation of post-correlation software for delay observable generation and multiparameter estimation of the baseline and instrumental parameters.

## VII. Outlook

Project ARIES has now entered its second phase of demonstration experiments. The transportable antenna is currently deployed at JPL and will occupy several sites throughout the seismically complex region of Southern California in the near future. The baselines to be surveyed in this second phase will range from 100 to 300 km in length. These baselines are particularly important since some geophysicists now believe that the crustal uplifting due to rock dilatancy, which is possibly premonitory to earthquakes, can be observed in the regions spanning a few hundred kilometers (Refs. 7 and 8). With these longer baselines, however, new challenges for Project ARIES must be met in order to achieve a system accuracy of 1–3 cm. First, the troposphere, ionosphere, and space plasma will introduce appreciable uncertainties in the time delay, since raypath dissimilarities will be greater for widely spaced antennas. Calibration of these differential propagation media delays will require special-purpose instrumentation such as the water vapor microwave radiometer (for calibrating the “wet” troposphere) and dual-frequency reception (for calibrating charged-particle effects). For these longer baselines, radio source locations and Earth orientation parameters must be calibrated or modeled at the 0.03 arc second level. Such calibration should be obtainable from independently conducted interferometry experiments on *intercontinental* baselines. With these anticipated improvements, the ARIES interferometer should be capable of three-dimensional measurements of baselines spanning hundreds of kilometers with an accuracy of a few centimeters.

## Acknowledgments

The authors wish to acknowledge the contributions of many JPL colleagues, particularly J. L. Fanselow, R. A. Preston, M. A. Slade, D. W. Trask, and J. G. Williams for valuable discussions; M. W. Eltgroth and K. F. Fox for data reduction; R. J. Wallace and J. A. Carpenter for assistance in the implementation of the ARIES station; B. B. Johnson for experiment assistance; and W. R. Bollinger for the ground survey at Goldstone. We also appreciate the hospitality of the National Radio Astronomy Observatory for use of the Mark II Data Processor with special thanks to B. G. Clark and B. Rayhrer. In addition, we wish to thank the Satellite Communications Agency, U. S. Army, Fort Monmouth, N. J., for the transfer of the surplus transportable 9-m station to NASA/JPL; the NASA Office of Tracking and Data Acquisition for cooperation in scheduling ARIES experiments; and the personnel of the Mars Deep Space Station for experiment conduct.

## References

1. Cohen, M. H., "Accurate Positions for Radio Sources," *Astrophys. Lett.*, Vol. 12, p. 81, 1972.
2. Hinteregger, H. F., et al., "Precision Geodesy via Radio Interferometry," *Science*, Vol. 178, p. 396, 1972.
3. Ryle, M., and Elsmore, B., "Astrometry with the 5-km Radio Telescope," *Mon. Not. Roy. Astron. Soc.*, Vol. 164, p. 223, 1973.
4. Shapiro, I. I., et al., "Transcontinental Baselines and the Rotation of the Earth Measured by Radio Interferometry," *Science*, Vol. 186, p. 920, 1974.
5. Thomas, J. B., et al., "A Demonstration of an Independent-Station Radio Interferometry System with 4-cm Precision on a 16-km Baseline," submitted to *J. Geophys. Res.*, 1974.
6. Nur, A., "Dilatancy, Pore Fluids, and Premonitory Variations of  $t_s/t_p$  Travel Times," *Bull. Seism. Soc. Am.*, Vol. 62, p. 1217, 1972.
7. Whitcomb, J. H., Garmany, J. D., and Anderson, D. L., "Earthquake Prediction: Variations of Seismic Velocities Before the San Fernando Earthquake," *Science*, Vol. 180, p. 632, 1973.
8. Anderson, D. L., and Whitcomb, J. H., "Time Dependent Seismology," *J. Geophys. Res.* (in press).
9. Shapiro, I. I., and Knight, C. A., "Geophysical Applications of Long Baseline Radio Interferometry," in *Earthquake Displacement Fields and the Rotation of the Earth*, pp. 284-301, edited by L. Mansinha, D. E. Smylie, and A. E. Beck, Springer-Verlag, New York, 1970.
10. Clark, B. G., "The NRAO Tape Recorder Interferometer System," *Proc. IEEE*, Vol. 61, p. 1242, 1973.

11. Counselman, C. C., III, "Very-Long-Baseline Interferometry Techniques Applied to Problems of Geodesy, Geophysics, Planetary Science, Astronomy, and General Relativity," *Proc. IEEE*, Vol. 61, p. 1225, 1973.
12. Cohen, M. H., "Introduction to Very-Long-Baseline Interferometry," *Proc. IEEE*, Vol. 61, p. 1192, 1973.
13. Thomas, J. B., "An Analysis of Long Baseline Radio Interferometry, Part III," in *The Deep Space Network Progress Report*, Technical Report 32-1526, Vol. XVI, pp. 47-64, Jet Propulsion Laboratory, Pasadena, Calif., Aug. 15, 1973.
14. Moran, J. M., "Very Long Baseline Interferometric Observations and Data Reduction," Harvard College Observatory and Smithsonian Astrophysical Observatory preprint, 1974; to be published in *Methods of Experimental Physics*, Vol. XII, edited by N. Carleton, Academic Press, New York.
15. MacDoran, P. F., "Radio Interferometry for Study of the Earthquake Mechanism," *Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System, Stanford Univ. Publ. Geol. Sci.*, edited by R. L. Kovach and A. Nur, Vol. 13, p. 104, 1973.
16. MacDoran, P. F., "Radio Interferometry for International Study of the Earthquake Mechanism," *Acta Astron.*, Vol. 1, p. 1427, 1974.
17. Whitney, A. R., Ph.D. Thesis, Massachusetts Institute of Technology, 1974.
18. Rogers, A. E. E., "Very Long Baseline Interferometry with Large Effective Bandwidth for Phase Delay Measurements," *Radio Sci.*, Vol. 5, p. 1239, 1970.

**Table 1. Conventional survey baseline vector between the ARIES antenna (Site A and Site B) and the Mars antenna (ARIES minus Mars) in the CIO frame**

Baseline component	Site A, m	Site B, m
X	$221.89 \pm 0.02$	$221.73 \pm 0.02$
Y	$-172.11 \pm 0.03$	$-172.47 \pm 0.03$
Z	$-123.26 \pm 0.02$	$-123.51 \pm 0.02$
Total length $l$	$306.68 \pm 0.02$	$306.87 \pm 0.02$

**Table 2. Summary of interferometry experiments**

Experiment date	Site	Total duration of experiment, <sup>a</sup> h	Number of observations <sup>b</sup>	Number of sources observed	Number of fit parameters	RMS fit delay residual, ns	Unmodeled delay noise, ns
12/22/73	A	6.0	17	9	7	0.31	0.25
4/23/74	B	7.0	20	14	7	0.24	0.15
6/5/74	B	9.7	29	11	6	0.20	0.13
6/18/74	B	5.8	19	12	7	0.35	0.18

<sup>a</sup>Including antenna move times.

<sup>b</sup>Each observation approximately 10 minutes.

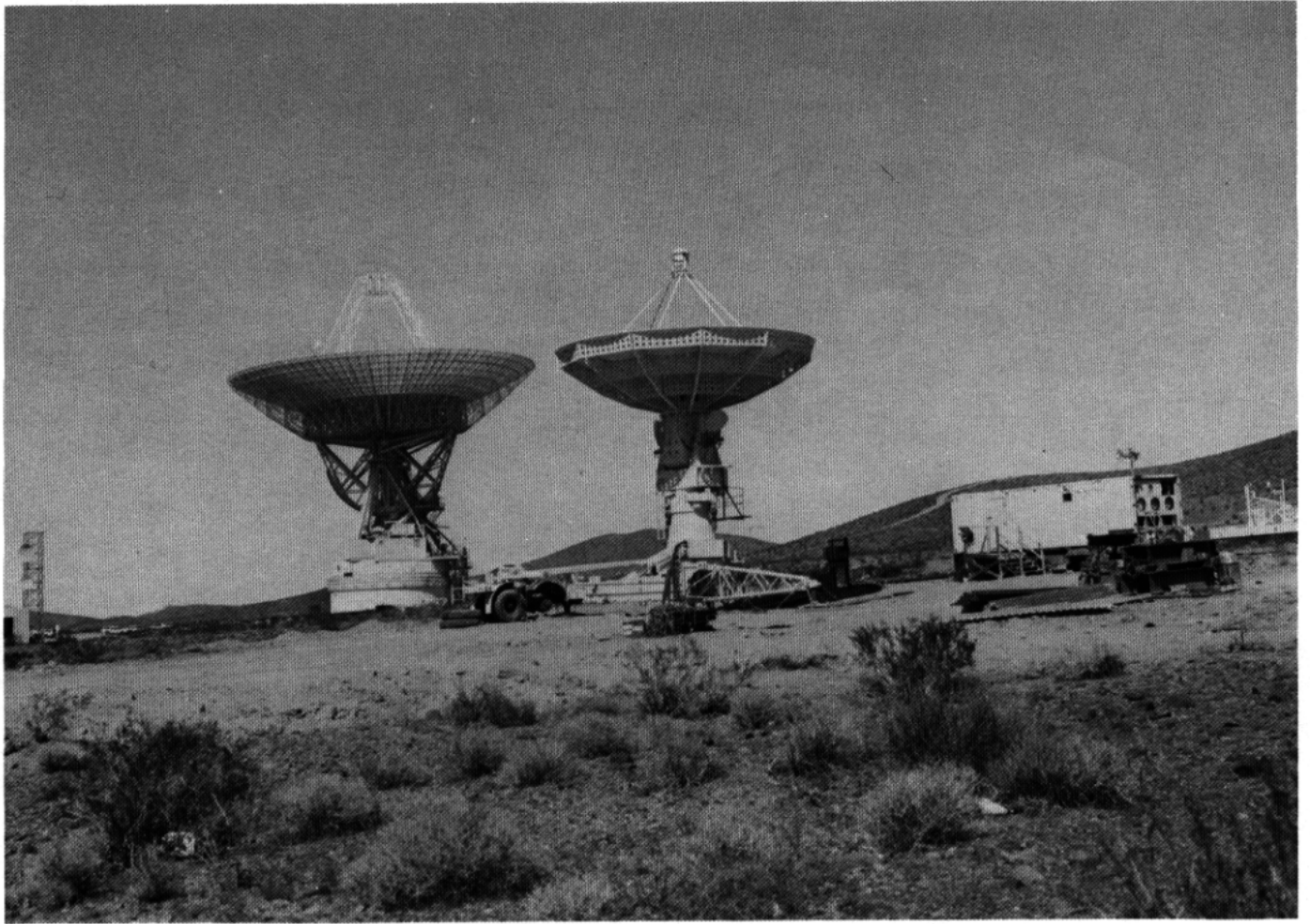
**Table 3. Interferometry results for the ARIES 307-m baseline experiments**

Experiment date	Site	X, m	Y, m	Z, m	$l$ , m
12/22/74	A	$221.79 \pm .07$	$-172.14 \pm .07$	$-123.33 \pm .07$	$306.64 \pm .07$
4/23/74	B	$221.70 \pm .04$	$-172.39 \pm .07$	$-123.57 \pm .06$	$306.82 \pm .07$
6/5/74	B	$221.72 \pm .04$	$-172.53 \pm .04$	$-123.52 \pm .04$	$306.90 \pm .04$
6/18/74	B	$221.72 \pm .06$	$-172.66 \pm .10$	$-123.57 \pm .08$	$306.99 \pm .10$
Weighted average	B	$221.71 \pm .03$	$-172.51 \pm .03$	$-123.54 \pm .03$	$306.90 \pm .03$

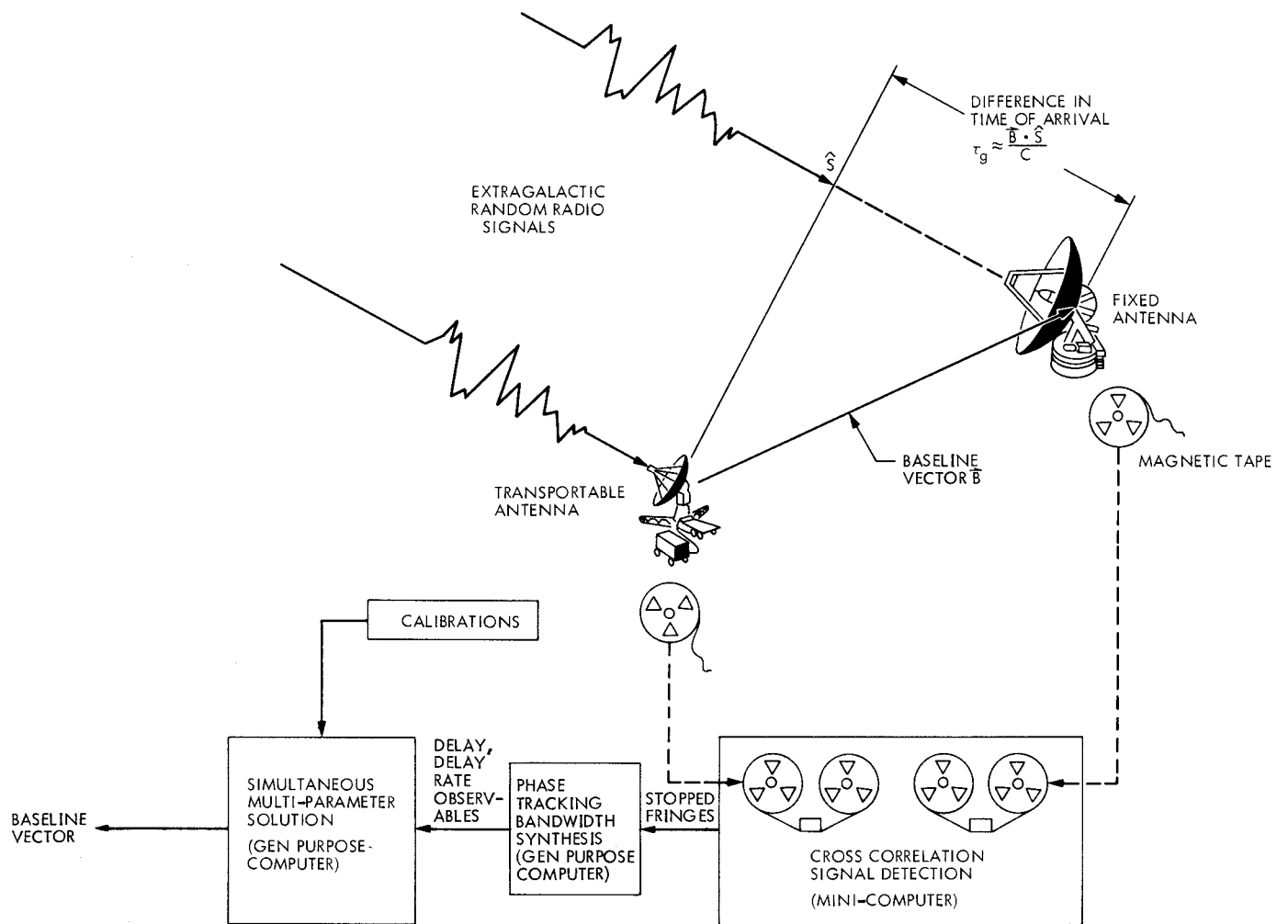
**Table 4. Comparison of the interferometry displacement vector between Sites A and B ( $B - A$ ) with the survey value**

Type data	$\Delta X$ , cm	$\Delta Y$ , cm	$\Delta Z$ , cm	$\Delta l$ , cm
Interferometry	$-8 \pm 8$	$-37 \pm 8$	$-21 \pm 8$	$26 \pm 8$
Survey <sup>a</sup>	$-16 \pm 1$	$-36 \pm 1$	$-25 \pm 1$	$19 \pm 1$
Interferometer -	$8 \pm 8$	$-1 \pm 8$	$4 \pm 8$	$7 \pm 8$

<sup>a</sup>The survey displacement vector is a special local measurement on a very short ( $\sim 0.5$  m) distance and thus possesses a smaller formal uncertainty ( $\lesssim 1$  cm) than the values quoted in Table 1.



**Fig. 1. The 307-m baseline between the 64-m Mars antenna (left) and the 9-m ARIES antenna (center); ARIES electronics and control trailer on right**



**Fig. 2. Schematic diagram of the Project ARIES transportable antenna interferometer system**

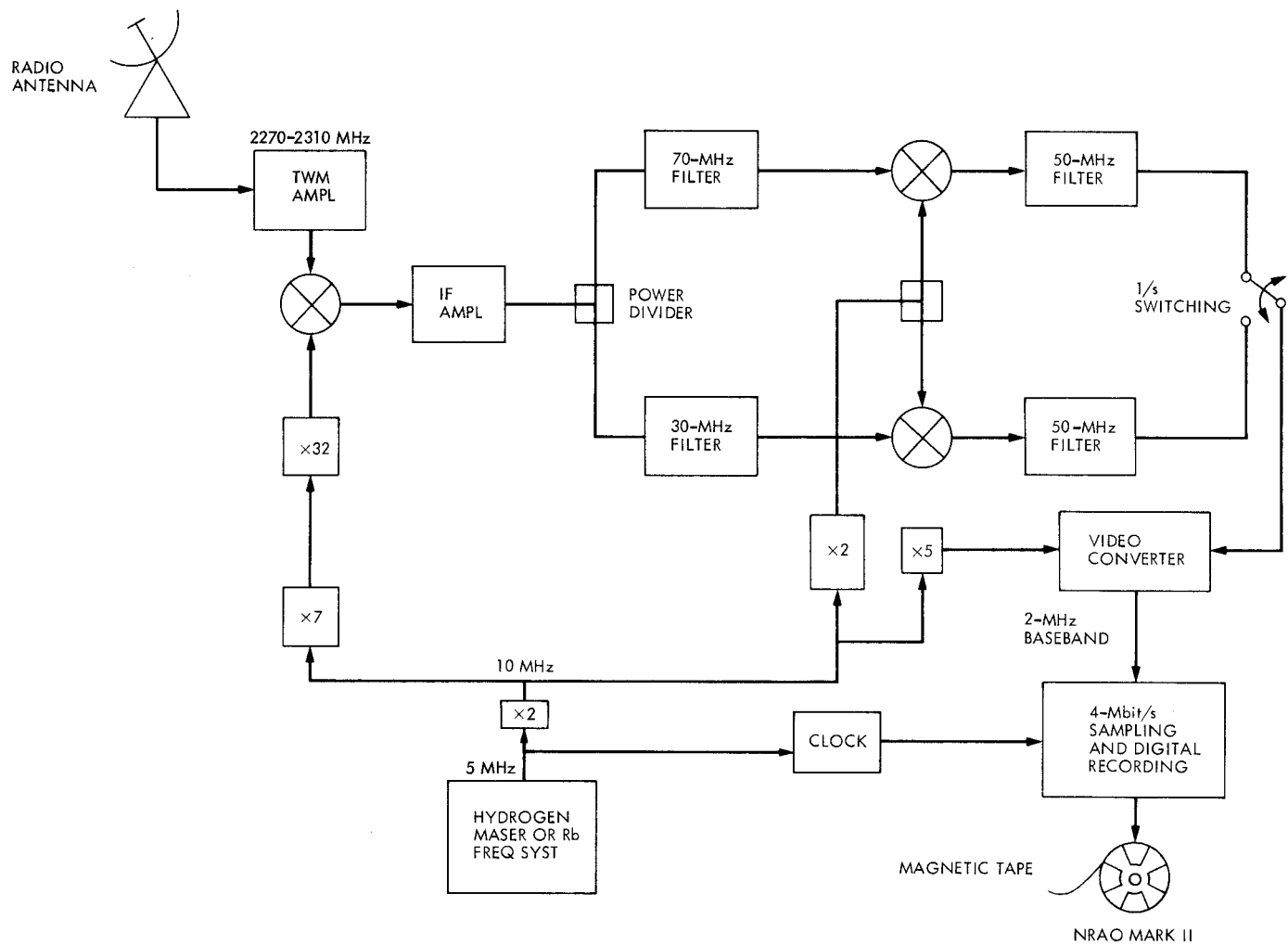


Fig. 3. Block diagram of ARIES radio system configuration

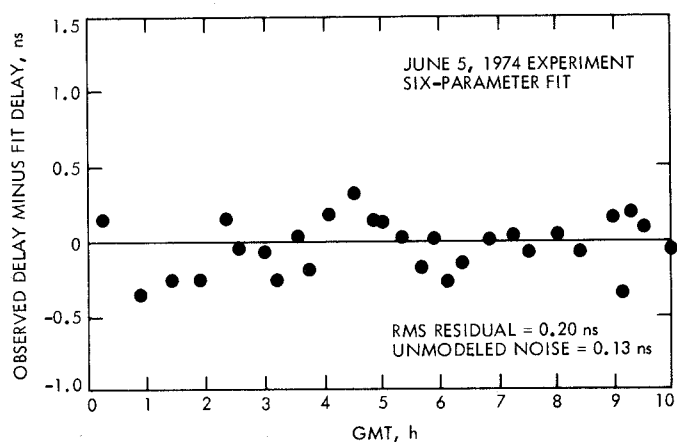


Fig. 4. Delay residuals for the ARIES experiment on June 5, 1974

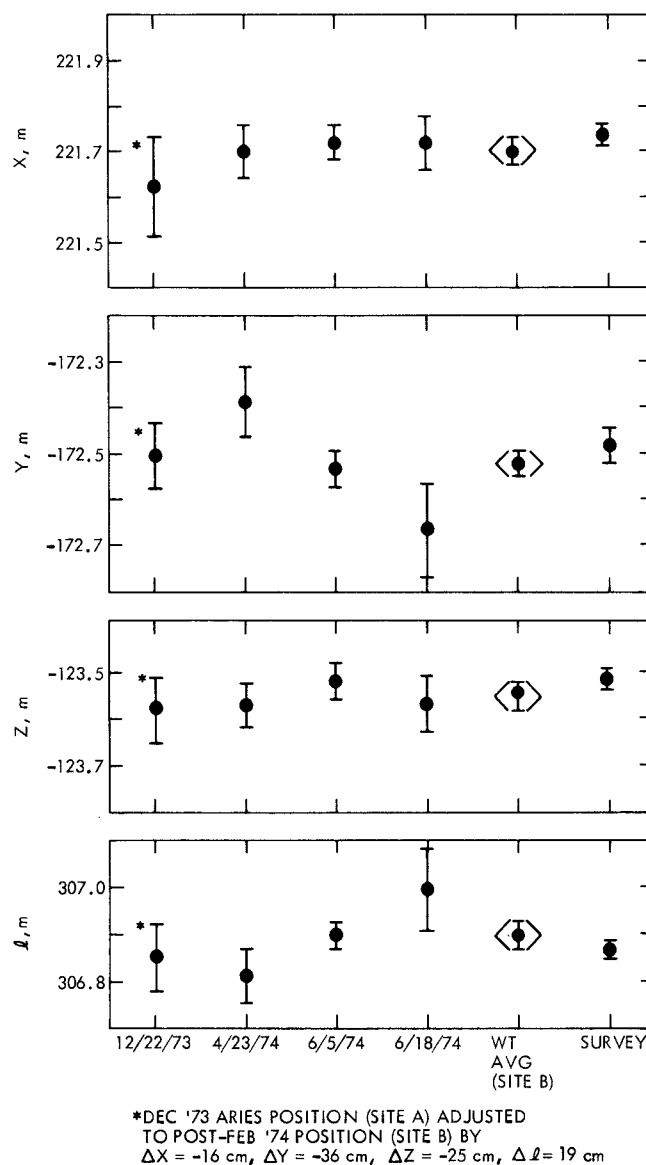


Fig. 5. ARIES 307-m baseline vector measurement: comparison of interferometer with survey